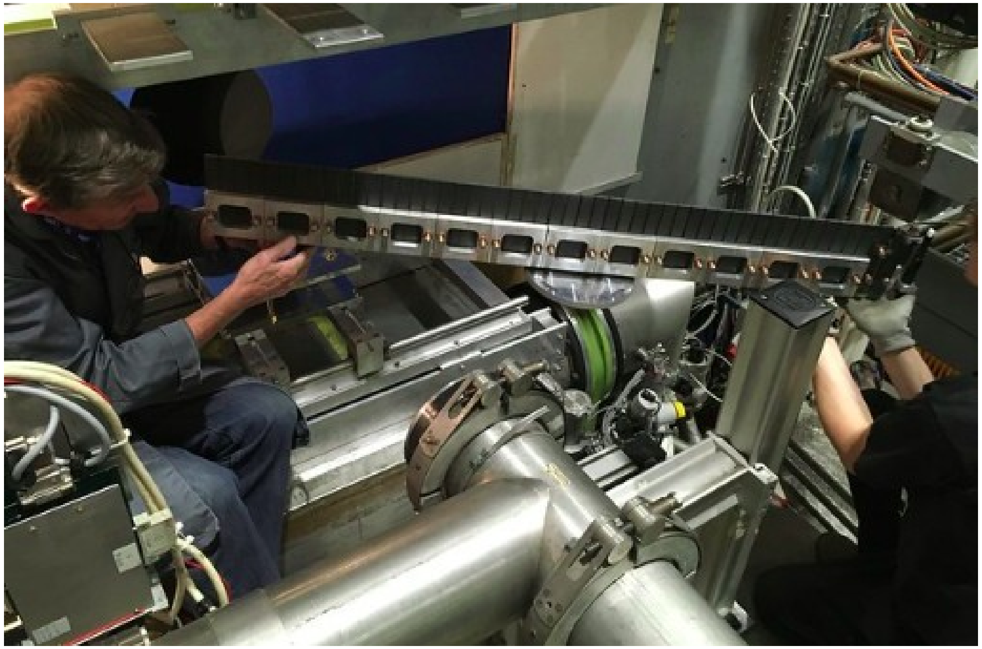
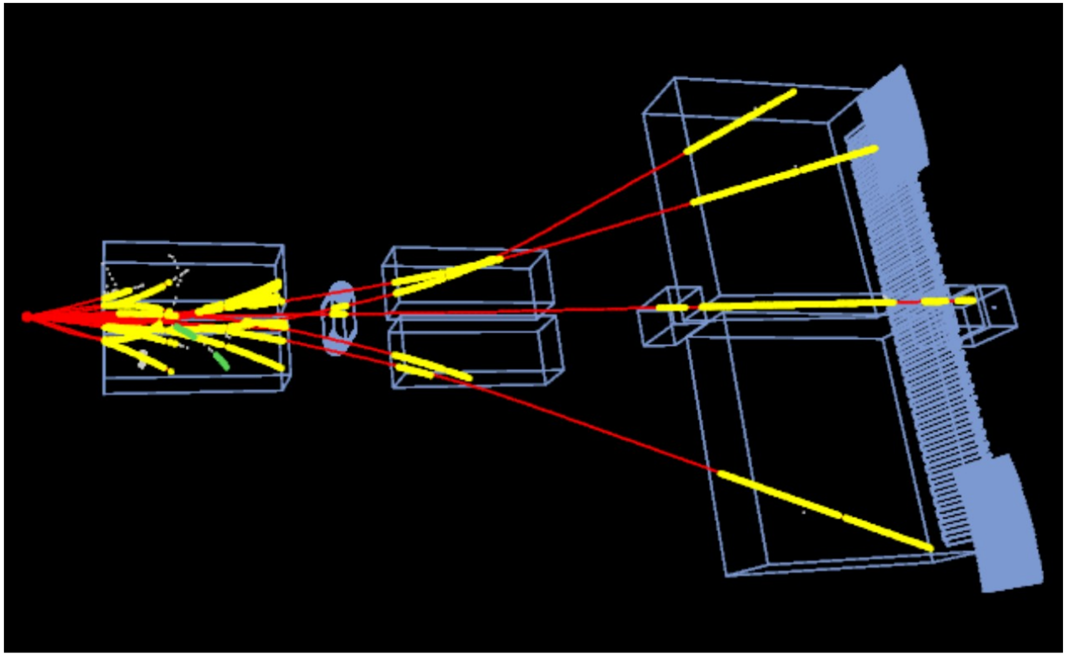
Hadron Production Measurements at NA61/SHINE





University of Colorado Boulder

Brant Rumberger

ICHEP 2020

7/29/20

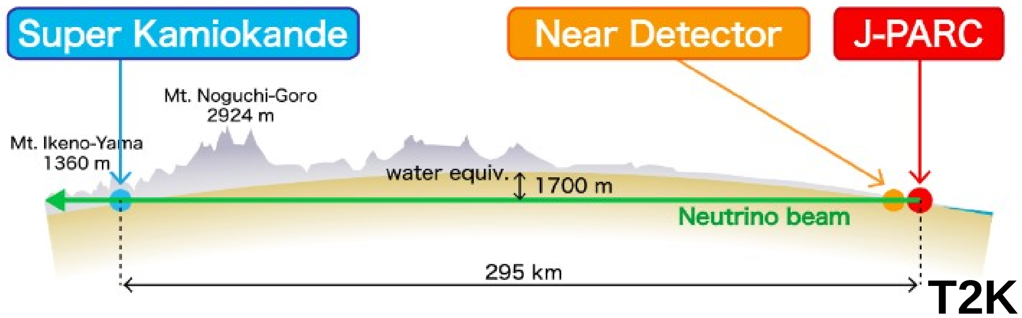
SHINE NA61

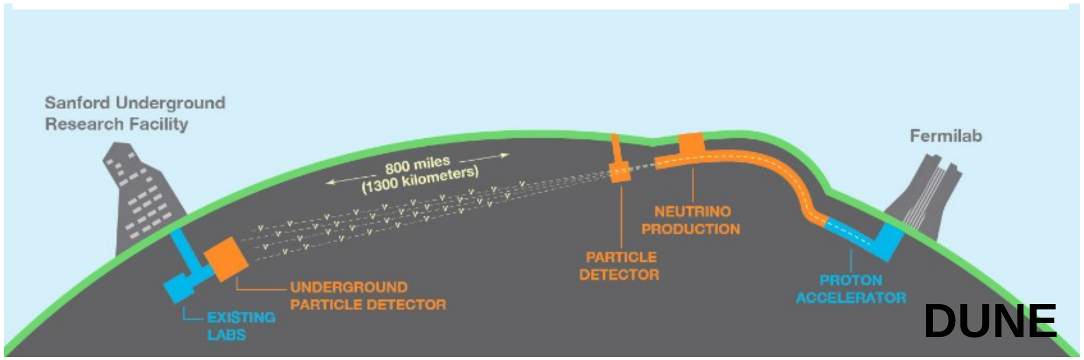
Overview

- Long Baseline Neutrino Oscillation Experiments
- Neutrino Beam Flux Uncertainties
- NA61/SHINE
- Current Measurements
- Upgrade & Future Measurements

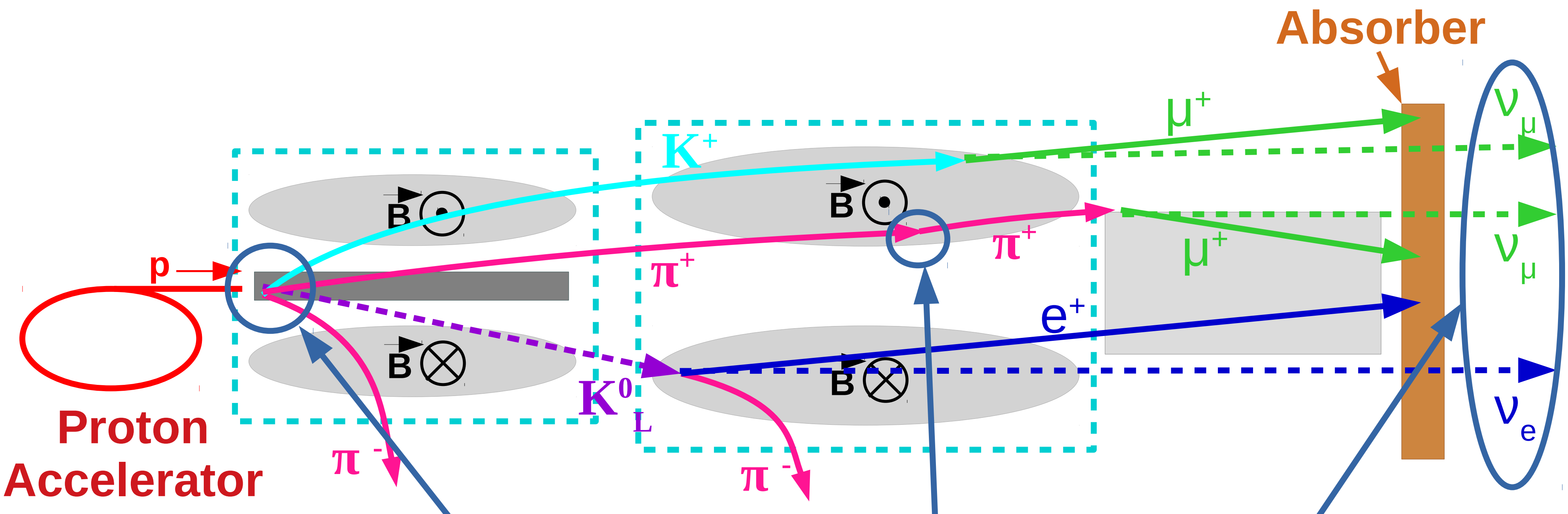
Long-Baseline Neutrino Oscillation Experiments

- Many prominent results over the past several years
- Active LB experiments:
  - T2K, NOvA, ...
- Future LB experiments:
  - DUNE, Hyper-K, …
  - Focus: Discovery & **precise parameter measurement**
- Future experiments require tight control of systematic uncertainties





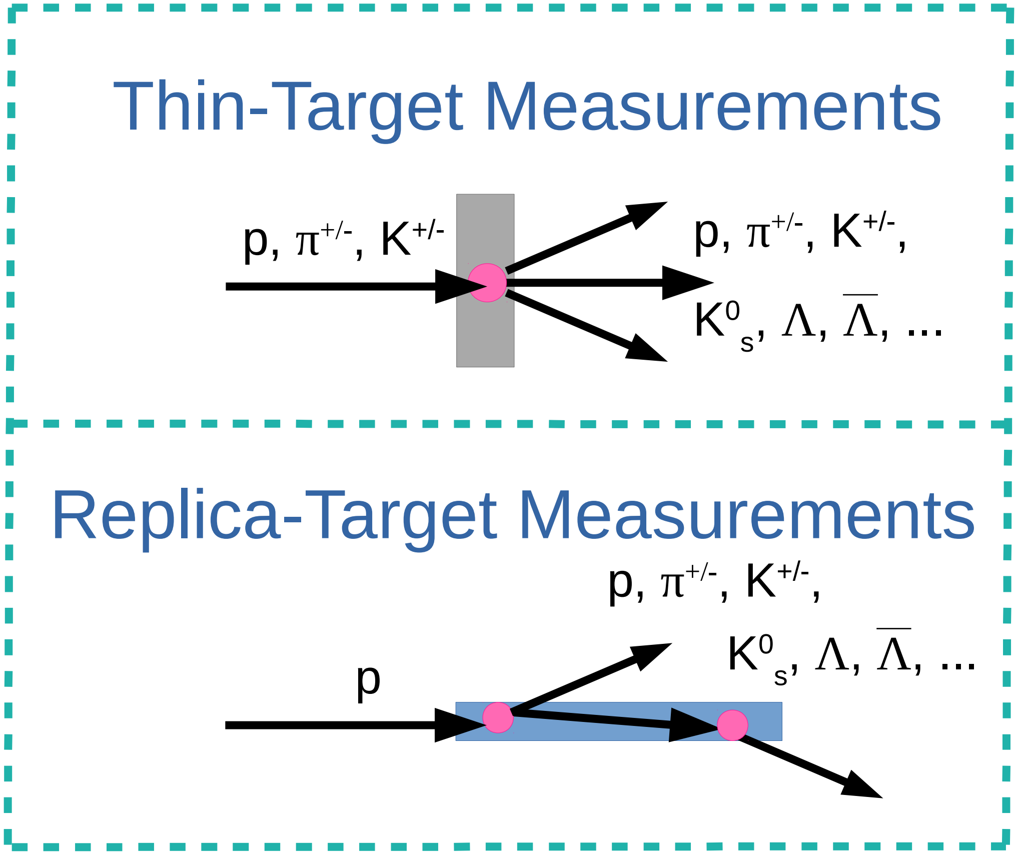
Neutrino Beam Flux Uncertainties

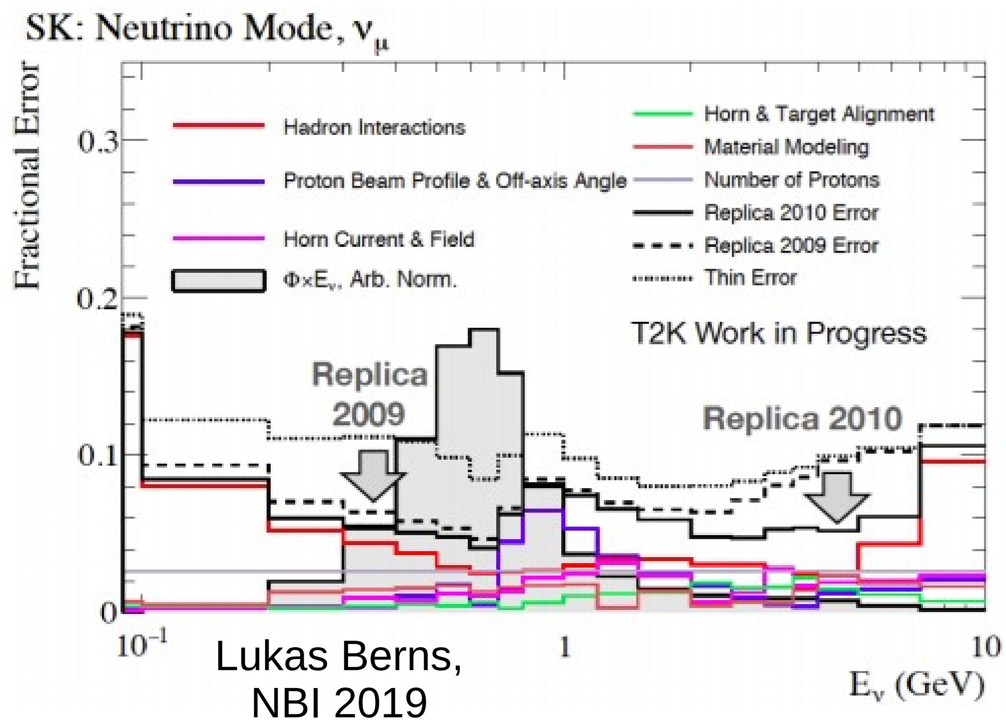


Neutrino beam content depends on primary & secondary hadron production in target & horns

No constraint data:
Large uncertainty!

Reducing Flux Uncertainty: Hadron Production Measurements



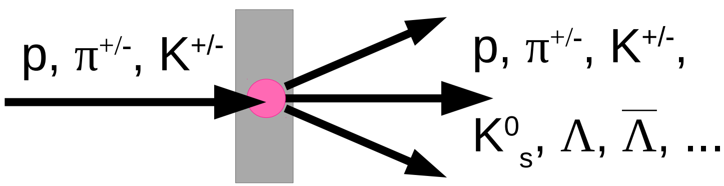


Beam reactions:

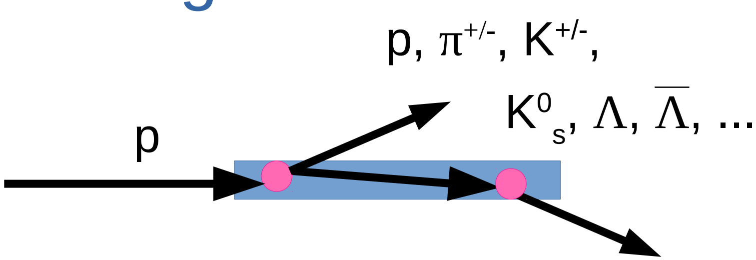
- T2K: 30 GeV/c protons on carbon
- NuMI: 120 GeV/c protons on carbon

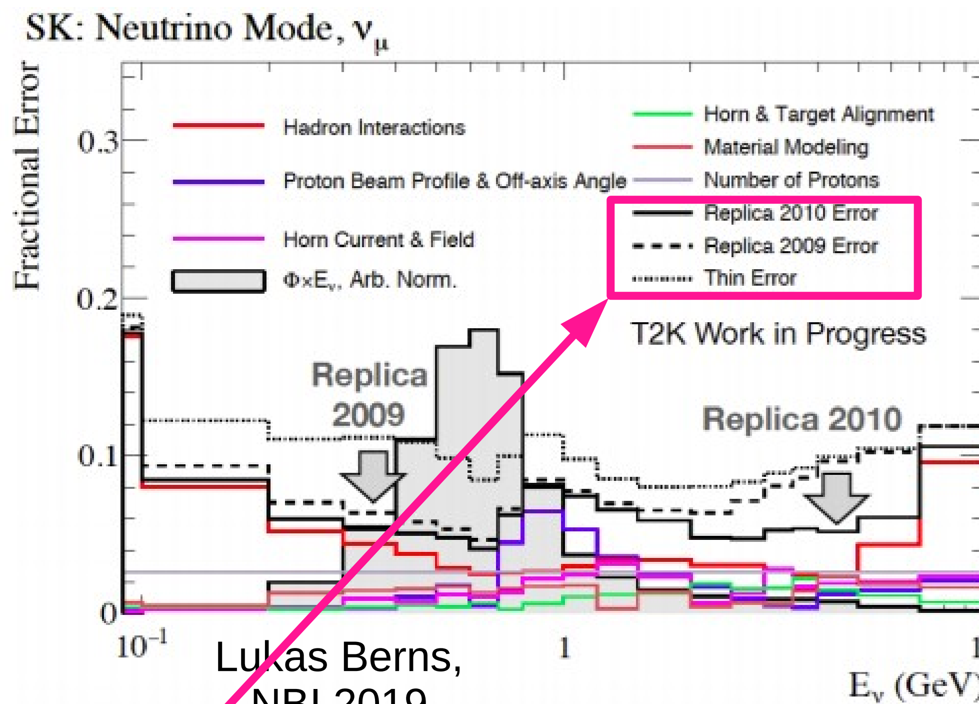
Reducing Flux Uncertainty: Hadron Production Measurements

Thin-Target Measurements



Replica-Target Measurements

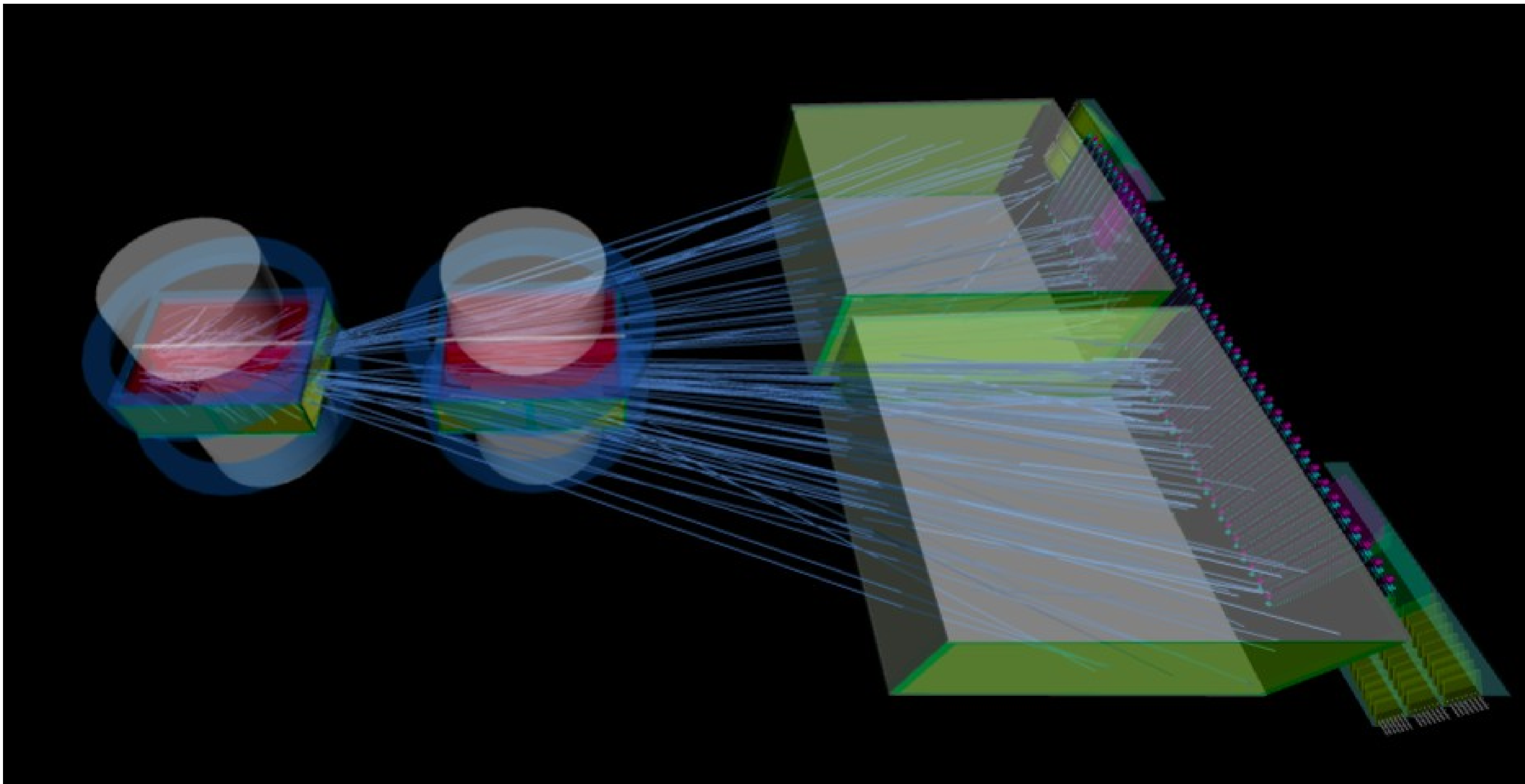




Lukas Berns, NBI 2019

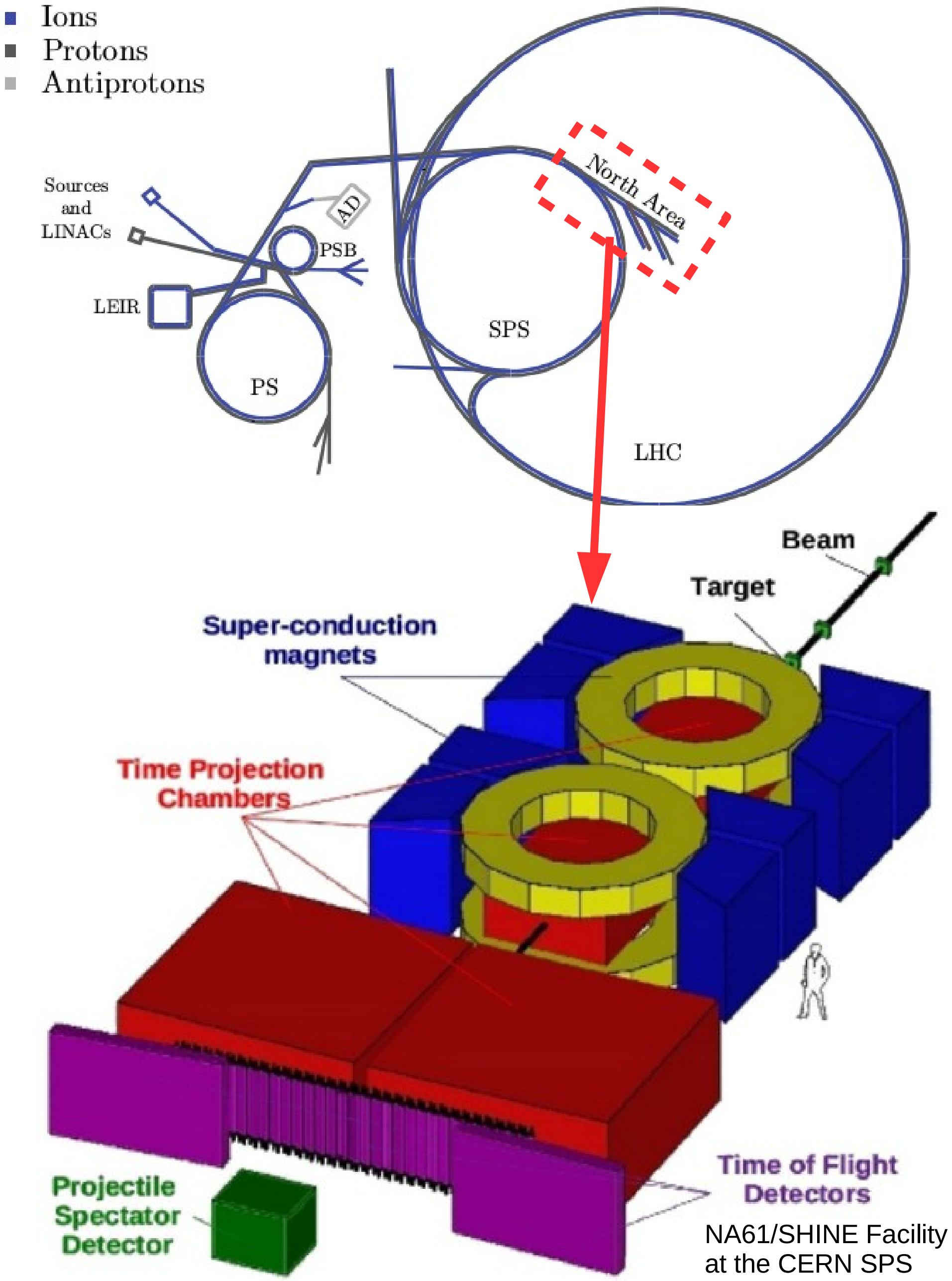
NA61/SHINE Data

NA61 / SHINE



NA61 / SHINE

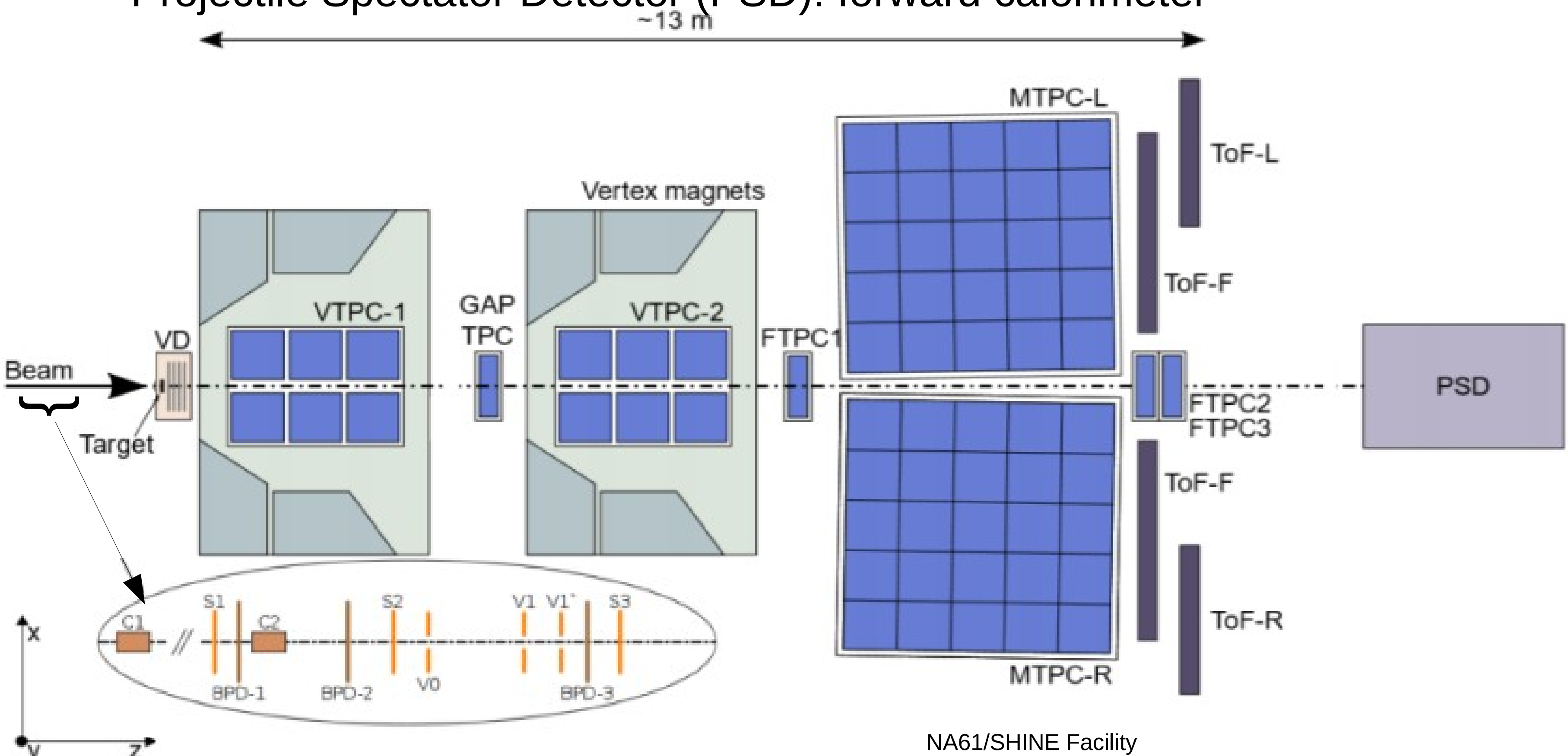
- **S**PS **H**eavy **I**on and **N**eutrino **E**xperiment
- Multi-faceted physics program
  - Heavy ions
  - Cosmic ray physics
  - Neutrino flux constraint measurements
- Beam options:
  - Primary 400 GeV/c protons
  - Secondary p, $K^{+/-}$, $\pi^{+/-}$, 13 - 350 GeV/c
- Target options:
  - Thin (~2 cm) targets, any material
  - Neutrino experiment replica targets



NA61/SHINE Facility at the CERN SPS

NA61/SHINE Detector

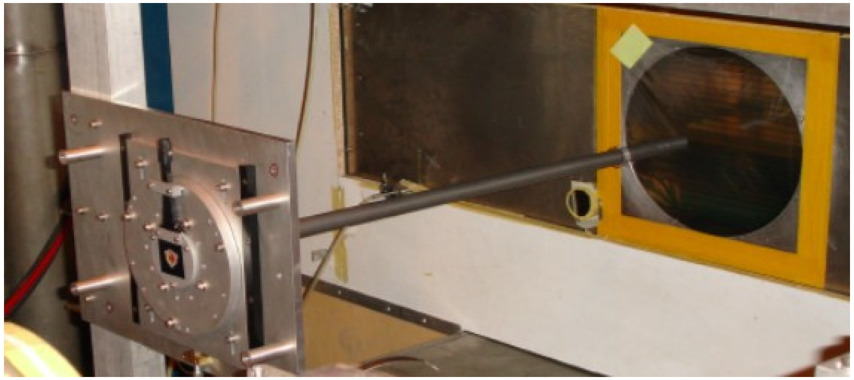
- 8 Time Projection Chambers: 3D tracking, dE/dx measurement
- 2 superconducting magnets: momentum determination
- Cerenkov detectors: beam particle identification
- 3 Time Of Flight walls: mass determination
- 3 beam position detectors
- Projectile Spectator Detector (PSD): forward calorimeter

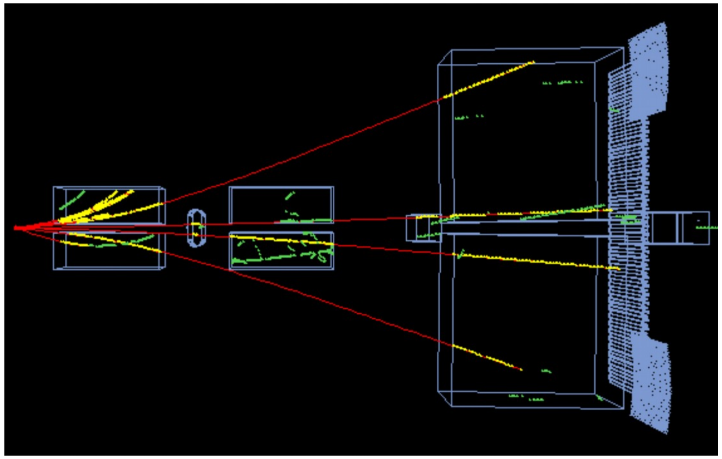


NA61/SHINE Facility
at the CERN SPS

NA61/SHINE Capabilities for Neutrino Experiment Measurements

- Thin target measurements
  - Target materials (C, Be, etc)
  - Horn materials (Al, Fe)
- Replica target measurements
  - T2K 90 cm
  - NuMI Medium Energy



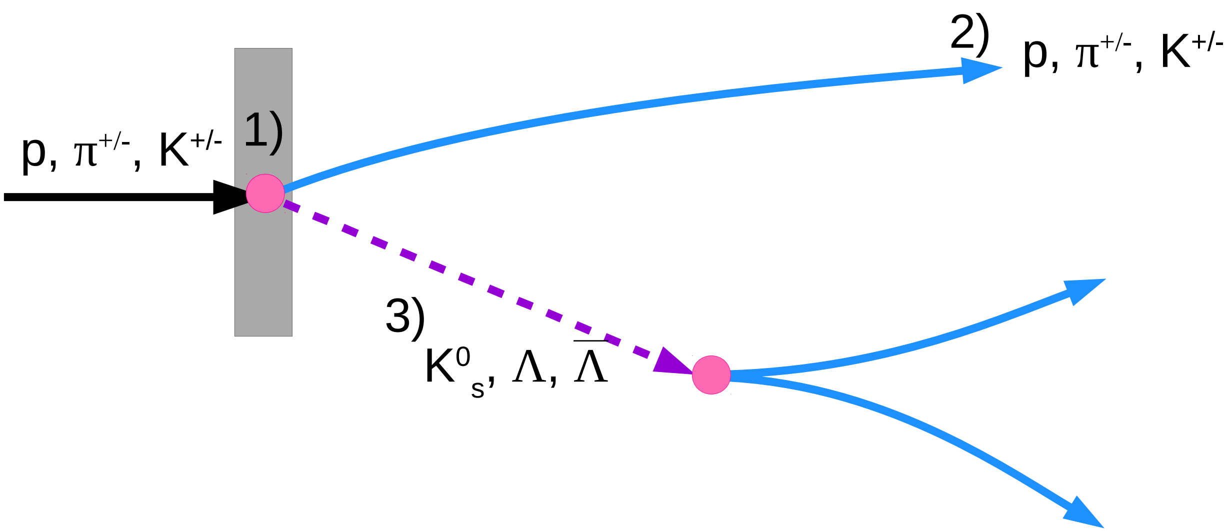


Recent Analysis Results: Thin Target Reactions

1) Total / inelastic / production cross-sections

2) Charged hadron yields

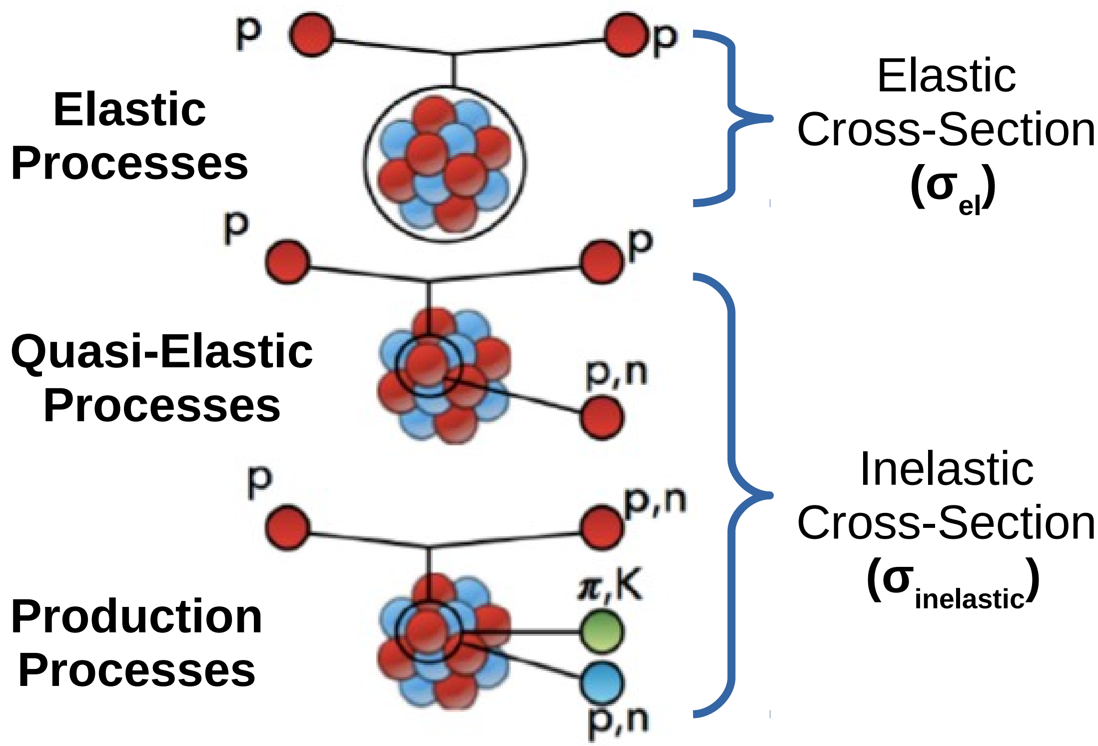
3) Neutral hadron yields



Thin-Target Results: Cross-Section

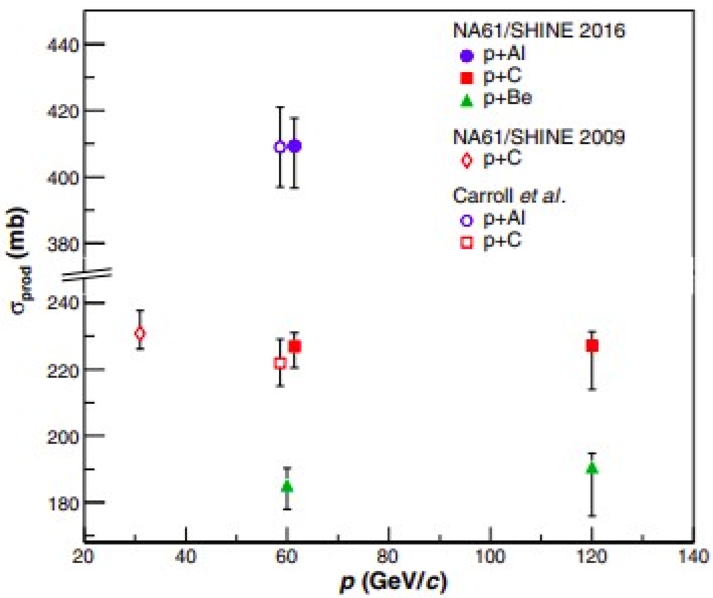
$$\sigma_{inelastic} = \sigma_{total} - \sigma_{elastic}$$

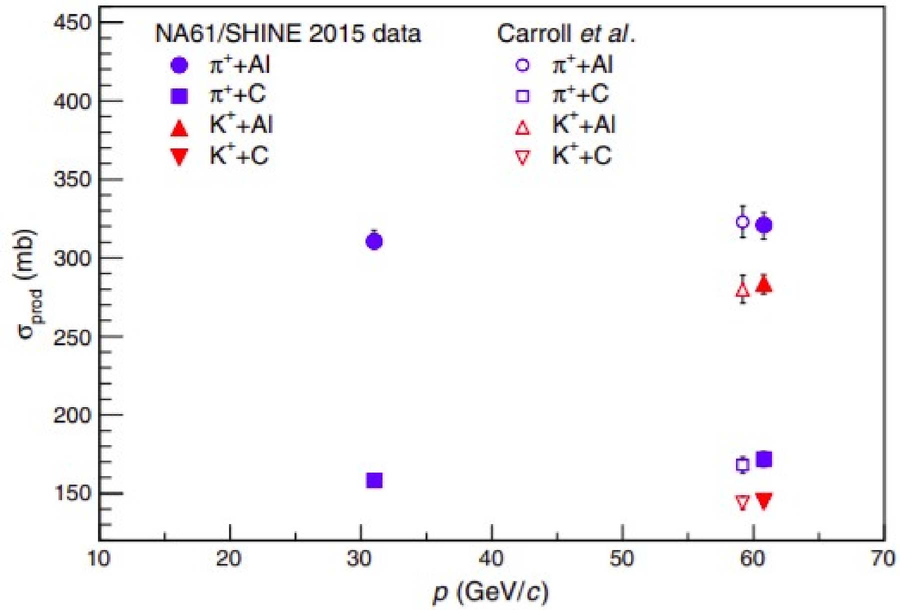
$$\sigma_{production} = \sigma_{inelastic} - \sigma_{QE}$$

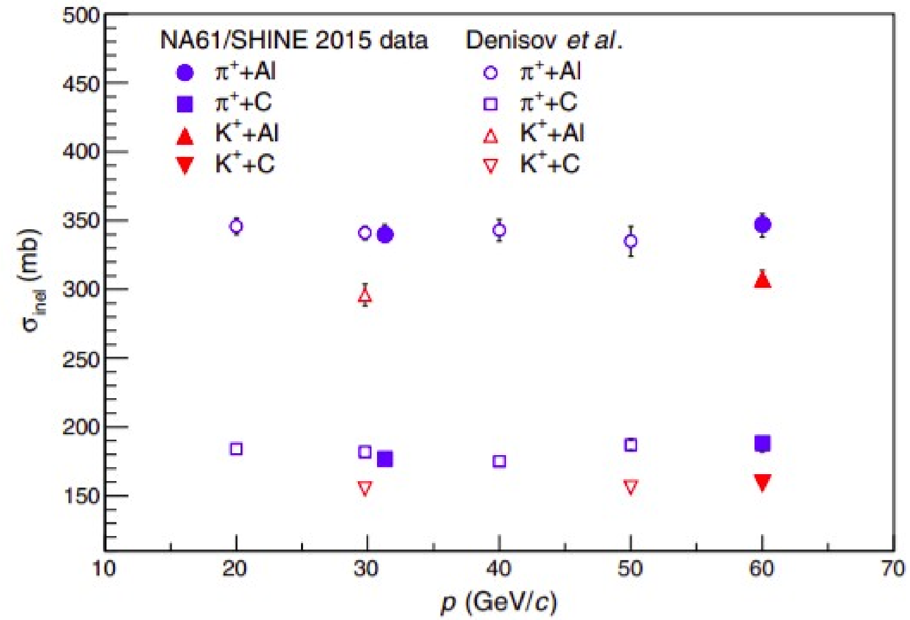


Thin Target Results: Cross-Section

- Inelastic & production cross-section measurements
- Used to weight hadron production to correct neutrino flux predictions
- **Phys. Rev. D 98, 052001 (2018):**
  - π^+ on C, Al (31 & 60 GeV/c)
  - π^+ on Be (60 GeV/c)
  - K^+ on C, Al (60 GeV/c)
- **Phys. Rev. D 100, 112001 (2019):**
  - p on C, Be (60 & 120 GeV/c)
  - p on Al (60 GeV/c)

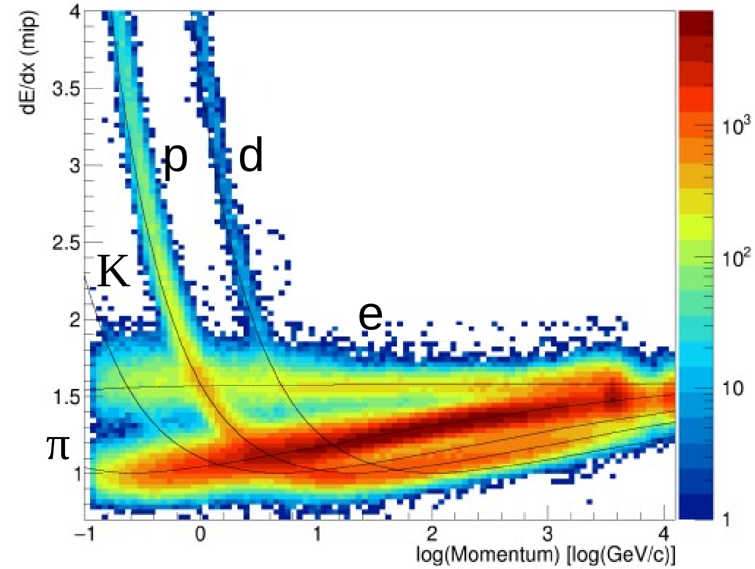






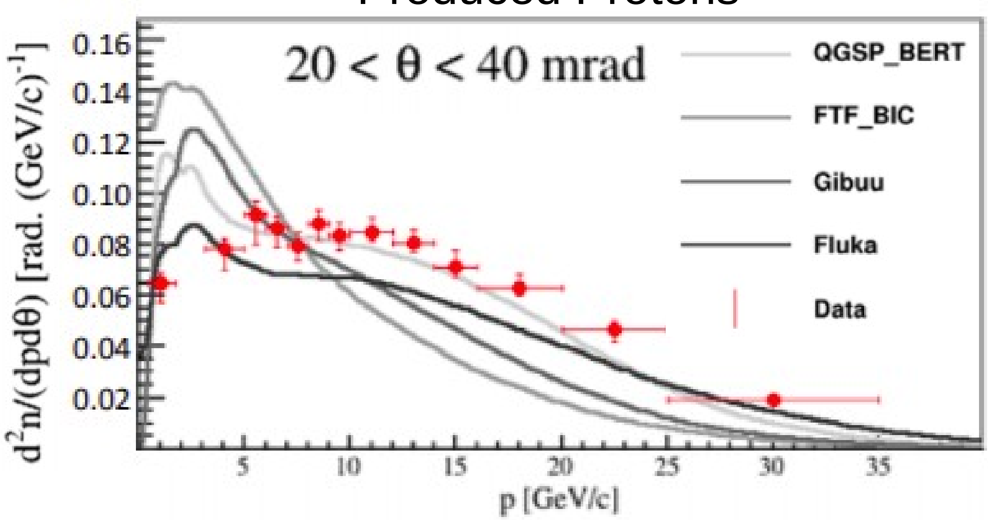
Thin Target Results: Charged Hadron Yield

- Obtain ID of produced particles using track momentum & dE/dx
- Charged tracks binned for analysis
- dE/dx fit performed in each bin
- Resulting multiplicities obtained for [p,θ] bins
- Used to improve hadron production models



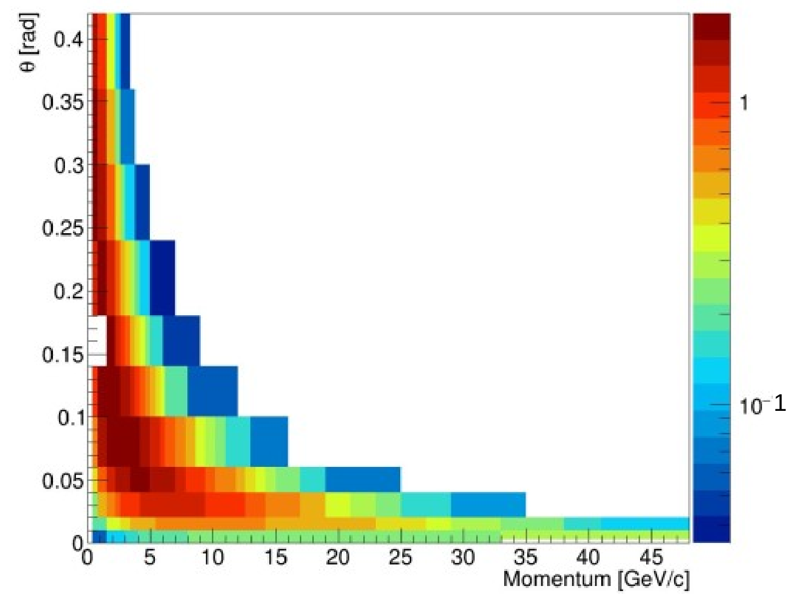
S. Johnson, Ph.D Thesis, 2019

Produced Protons



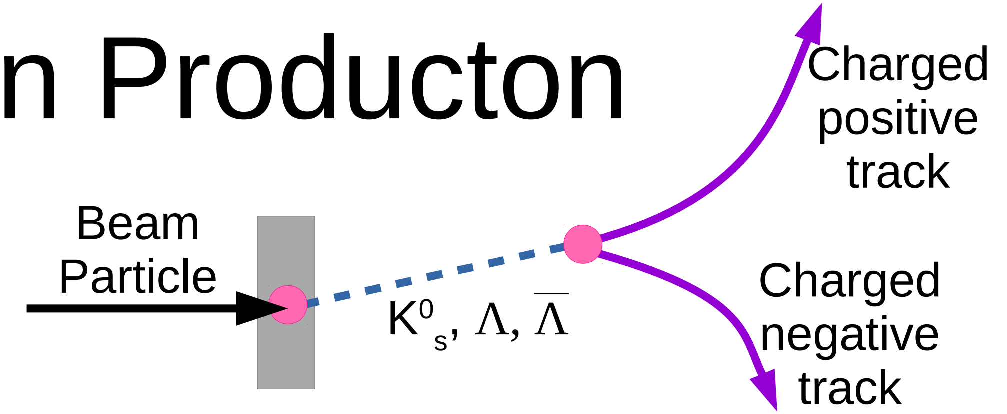
Phys. Rev. D100, 112004 (2019)

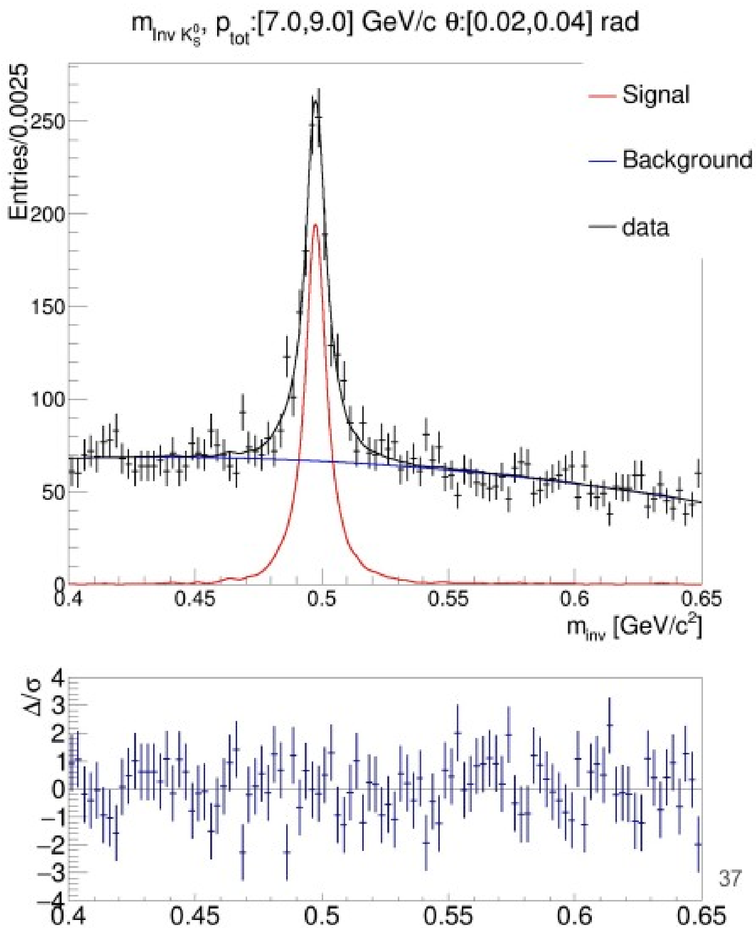
π^+ Yield: π^+ C, 60 GeV/c



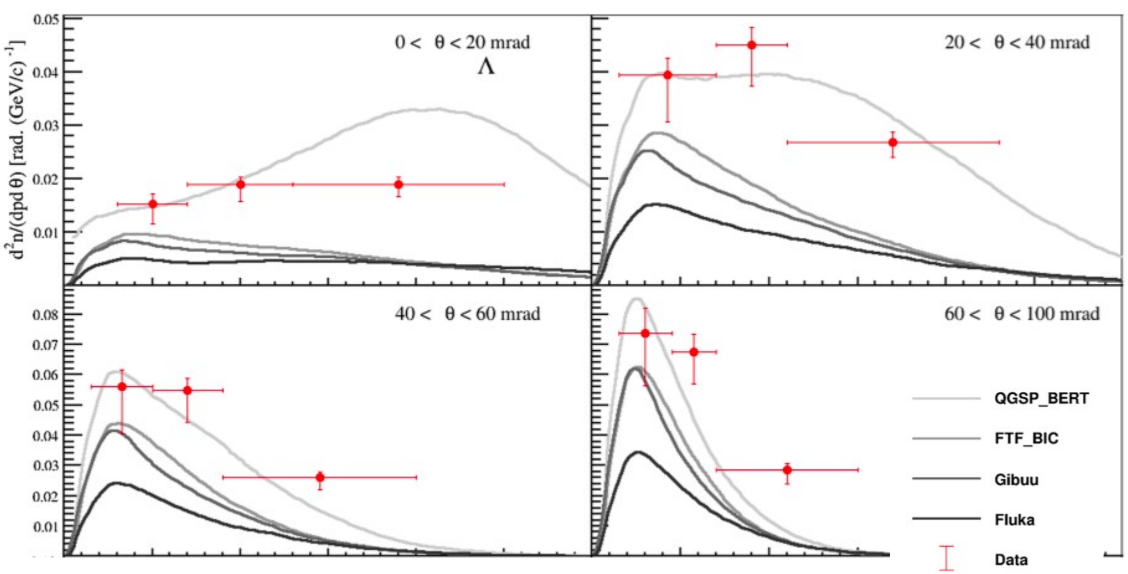
Thin Target Results: Neutral Hadron Producton

- Select + / - track pairs with small distance of closest approach
- Calculate invariant mass
- Fit signal for neutral particle yield





Λ Yield: π^+ C, 60 GeV/c



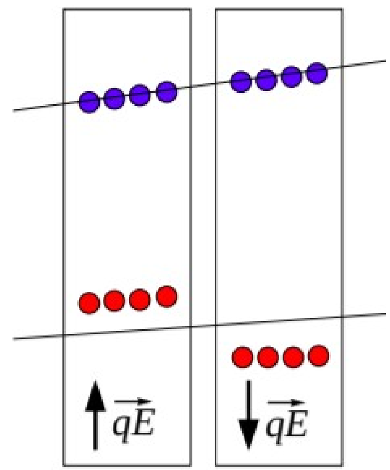
PHYS. REV. D 100, 112004

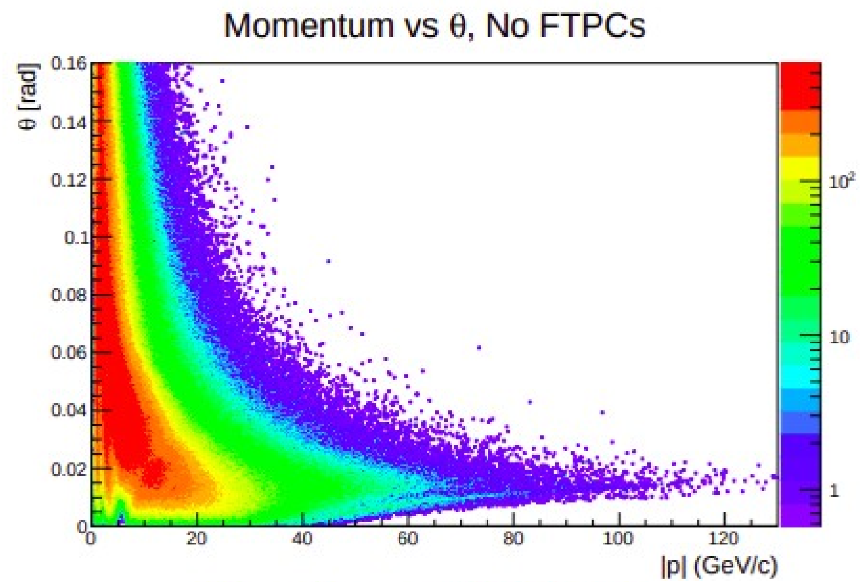
Current Ongoing Analyses

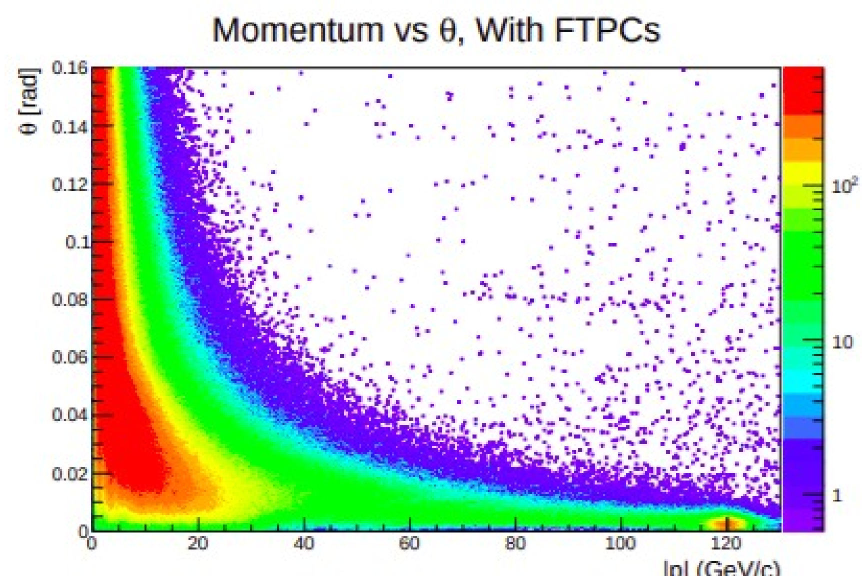
- p+T2K replica target (with high magnetic field)
  - Ongoing analysis of proton beam survival probability to measure production cross-section
- Thin-target p+C and p+Al at 60 GeV
  - Differential yield measurements for charged & neutral hadrons
- p+NuMI Medium Energy Replica Target
  - Differential yield measurements for charged & neutral hadrons

Closing the Forward Acceptance Gap

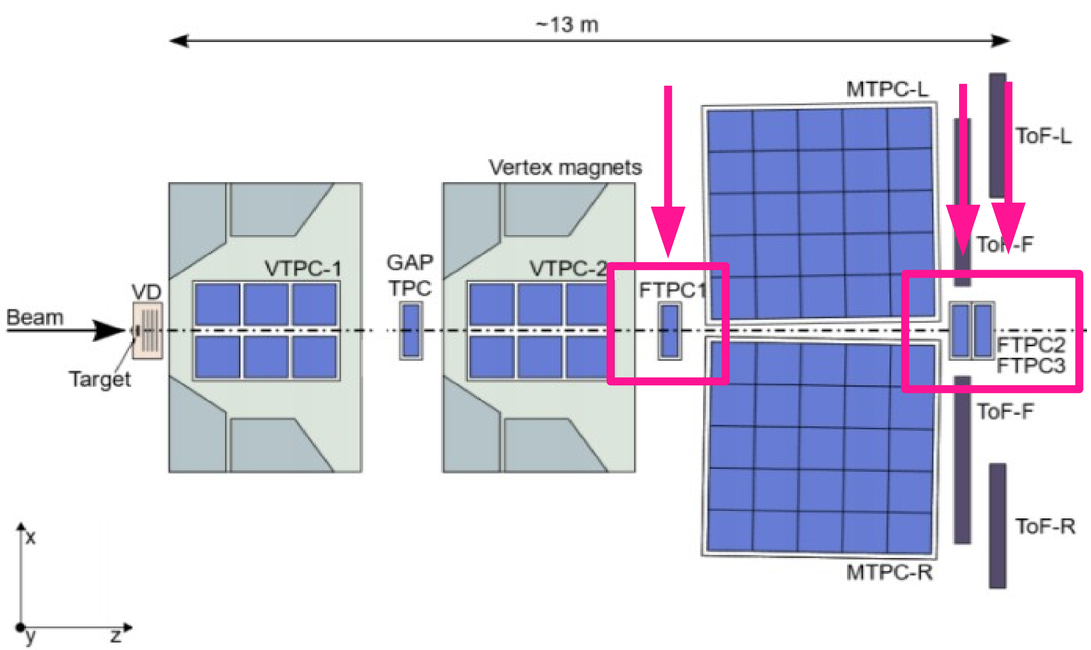
- Detector upgrade in 2017 significantly increased forward acceptance
- Forward Time Projection Chambers **(FTPCs)**
- Novel tandem field cage design for out-of-time track rejection
  - **JINST 15 P07013 (2020)**





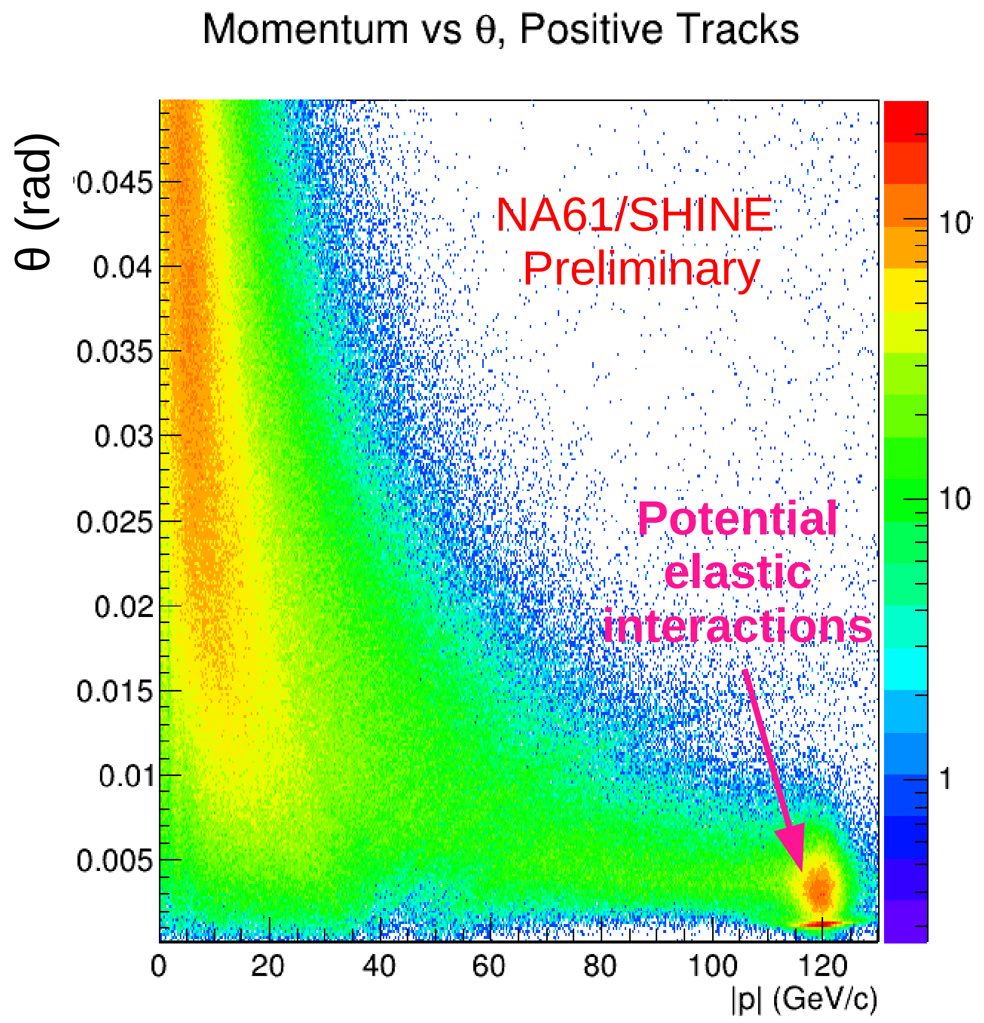


JINST 15 P07013 (2020)



Upcoming Thin Target Results for NuMI / DUNE

- p+C @ 120 GeV/c currently being analyzed
- NuMI beam energy & target material
- Charged hadron analysis to be completed in next few months
- Increased forward acceptance: potential for elastic cross-section measurement

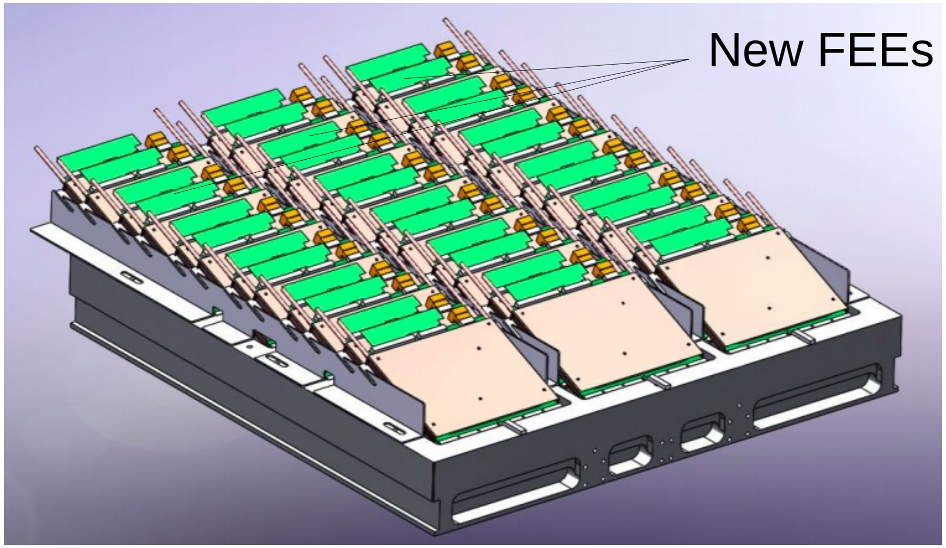


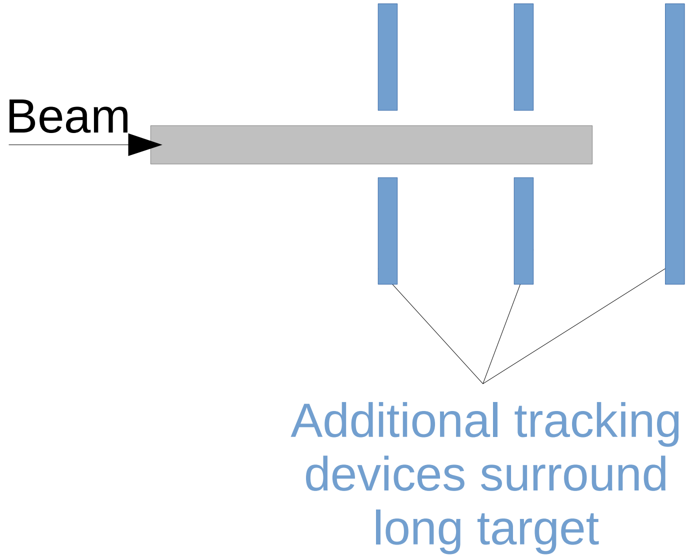
2017 Data to be analyzed (Last 3 with full forward phase space coverage)

Reaction	**Number of Triggers**
π^+ + Al 60 GeV/c	2.5 Million
π^+ + C 30 GeV/c	2.1 Million
π^- + C 60 GeV/c	3.5 Million
p + C 120 GeV/c	2.5 Million
p + Be 120 GeV/c	3.9 Million
p + C 90 GeV/c	3.1 Million

Upgrade Plans & 2021 Runs

- Major upgrades underway at NA61/SHINE
- DAQ upgrade: ~100 Hz → ~ 1KHz event rate
- TPC front-end electronics replacement: ALICE front-ends
- Low-energy beamline development
  - (1 – 13 GeV/c beams at NA61/SHINE)
- Long-target tracker possibilities being explored
- **Data taking resuming in 2021/2022**





Summary

- Neutrino beam flux is a leading systematic uncertainty for long-baseline neutrino experiments
- NA61/SHINE facility capable of taking relevant data to constrain neutrino flux
- Thin target & replica target results for several pertinent reactions published & used for oscillation analysis
- DUNE replica target data will hopefully be taken when design is finalized
- **Stay tuned!**

Thanks!

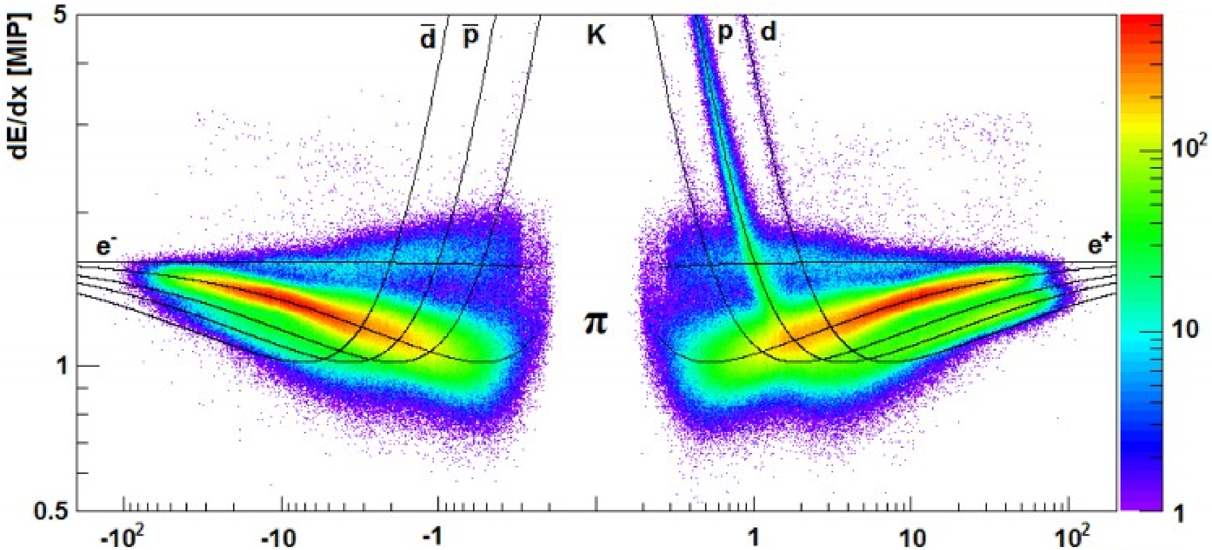
Thanks to the entire NA61 collaboration!

Funded by the US Dept. of Energy

BACKUP

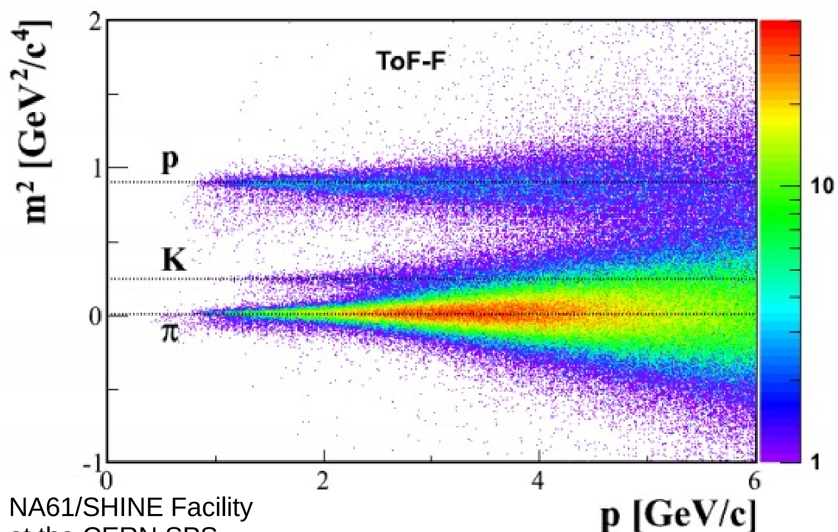
Particle Identification in NA61

- Performed via specific energy loss and time-of-flight analyses
- dE/dx: Sample charge deposited in detector along particle trajectory
  - Estimate mean dE/dx for each track
- TOF: Difference between trigger time and TOF scintillator hit time
  - Need high-precision scintillator hit time measurements (~100 ps)



Measured dE/dx vs log(p), with parameterized Bethe-Bloch curves overlayed:

$$-\left\langle \frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$



NA61/SHINE Facility at the CERN SPS

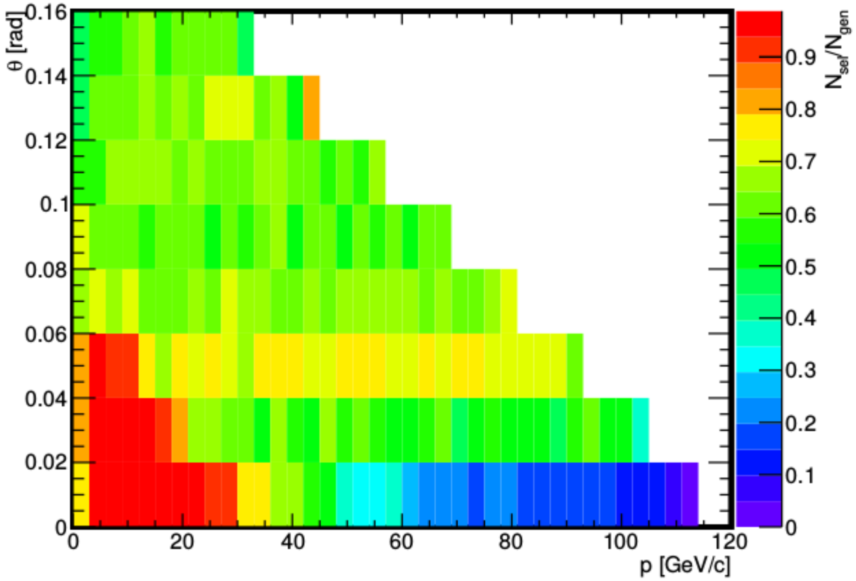
Measured mass from time-of-flight:

$$m^2 = p^2\left(\frac{c^2\, tof^2}{l^2} - 1\right)$$

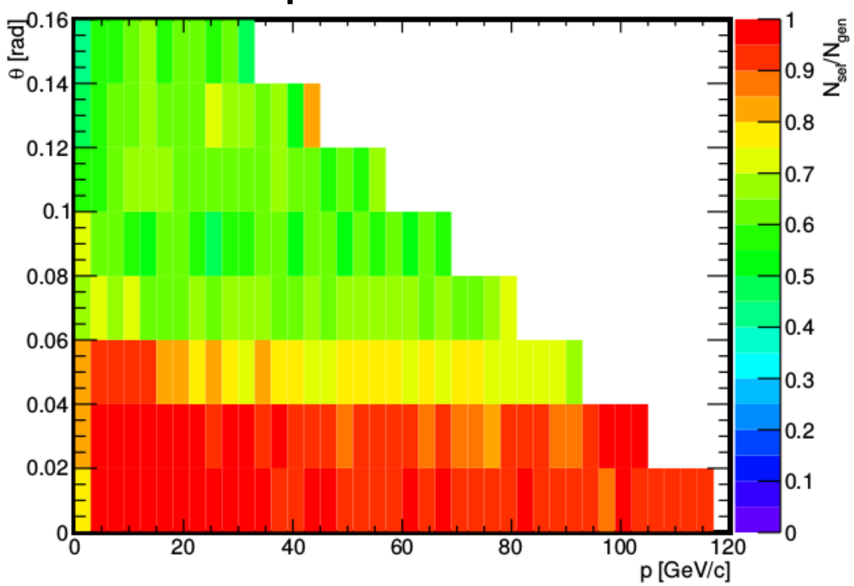
Additional Phase Space Coverage with FTPCs

NA61 Acceptance
(120 GeV/c p+C)

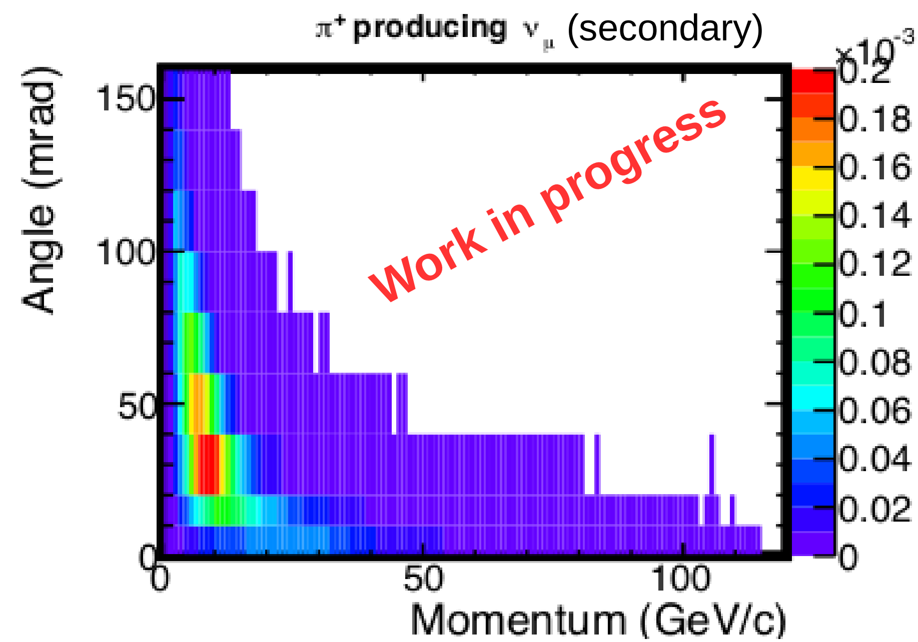
Old Acceptance (Pre-FTPCs)

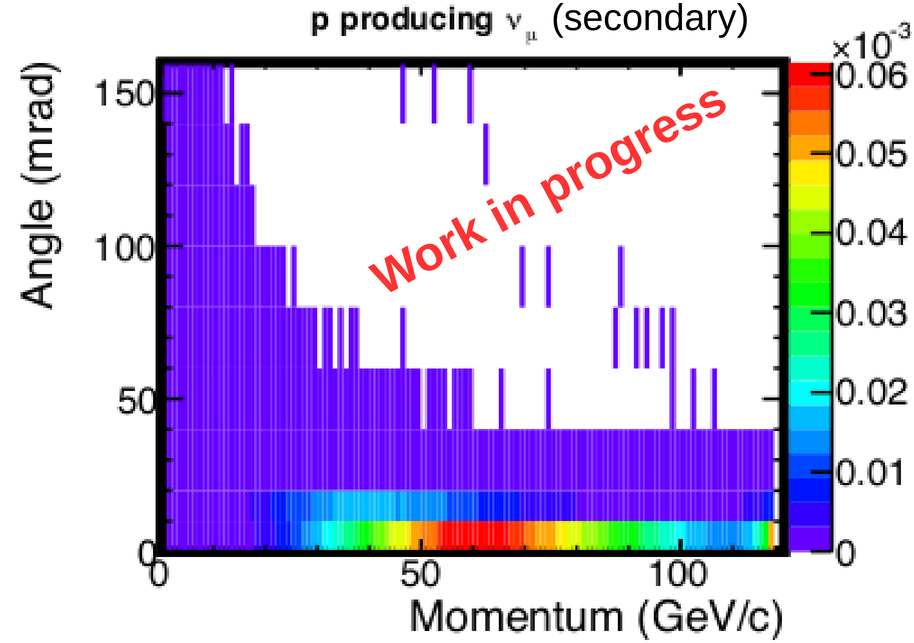


New Acceptance With FTPCs

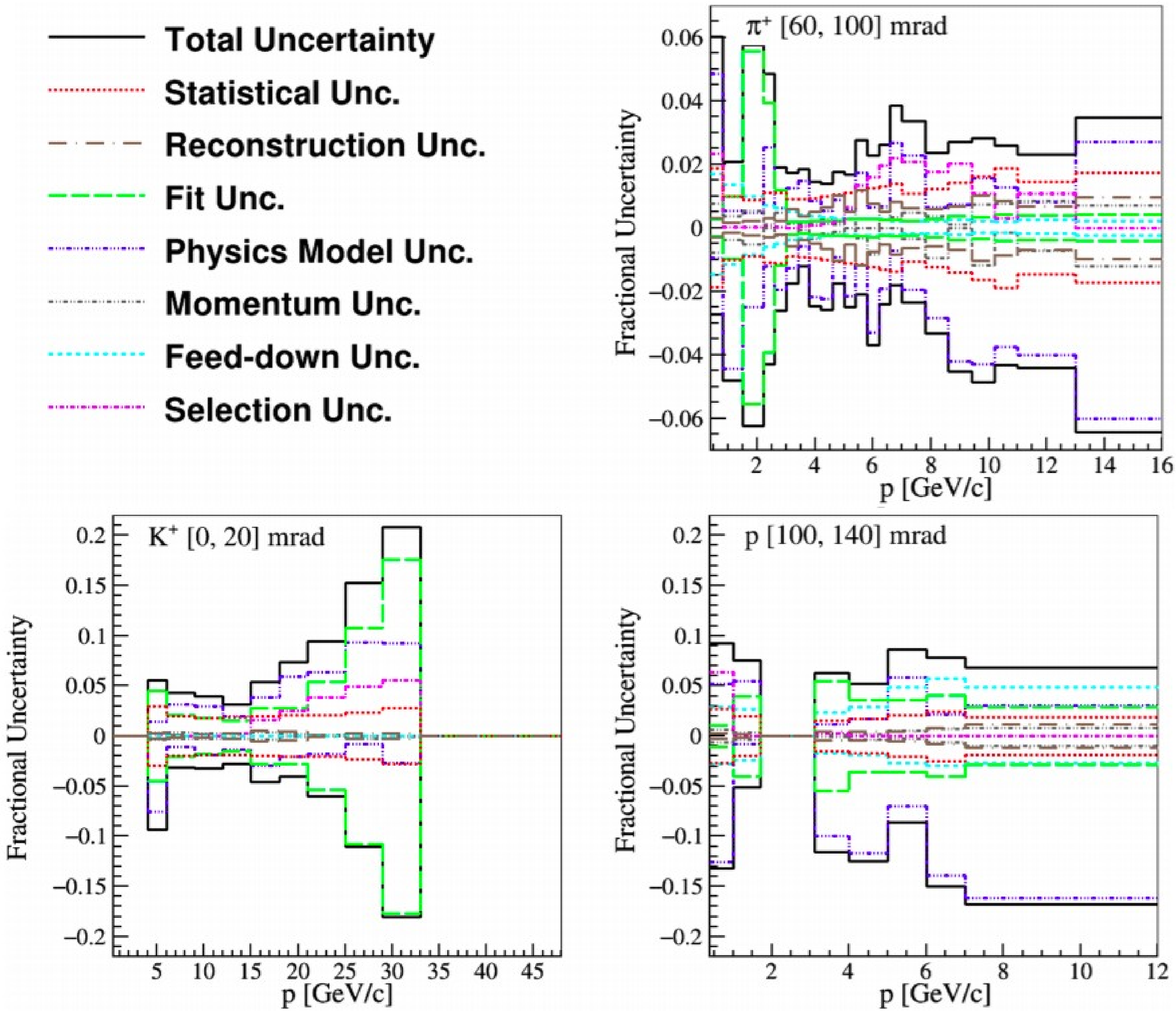


Example DUNE Neutrino Flux Contributors
(120 GeV/c proton beam)





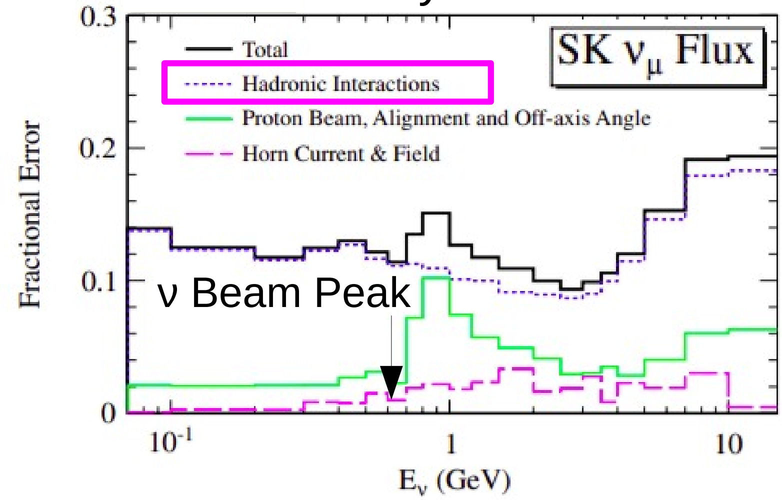
Thin-Target Results: Systematic Uncertainties



Neutrino Beam Flux Uncertainty

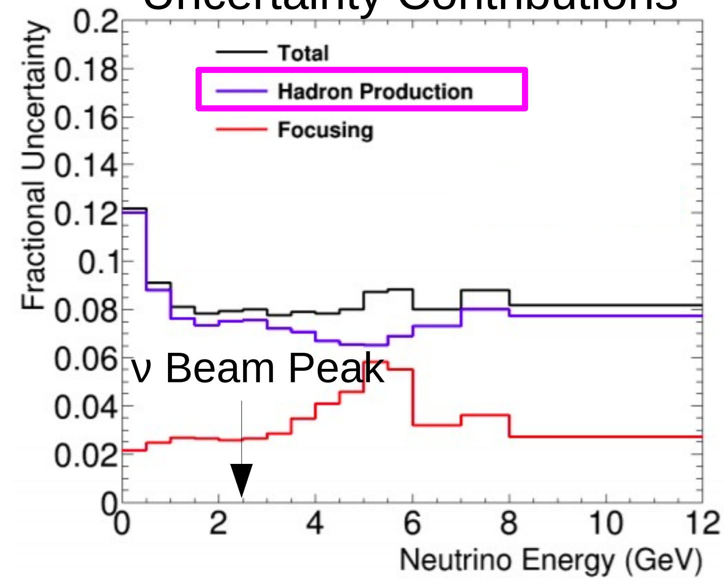
- Uncertainties on beam flux result in
  - Uncertainties on cross-section measurements
  - Uncertainties on oscillation parameter measurements
- Without **any** constraint data, hadron production uncertainty very large (20% – 50%)
- With current experimental data, uncertainties can still be as large as 8 – 12%

T2K Far Detector Flux Uncertainty Contributions



Phys. Rev. D 87, 012001 (2013)

DUNE Far Detector Flux Uncertainty Contributions



L. Fields, NA61
Beyond 2020 Workshop